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COMPARATIVE ANALYSIS OF DRAG REDUCTION FLOW EFFICIENCY THROUGH THE USE OF SURFACTANTS AND HIGH MOLECULAR POLYMER ADDITIVES

ANALIZA PORÓWNAWCZA EFEKTYWNOŚCI REDUKCJI OPORÓW PRZEPLYWU ZA POMOCĄ DODATKÓW WIELKOCZĄSTECzkOWYCH POLIMERÓW I SUBSTANCJI POWIERZCHNIOWO CZYNNYCH

Abstract

A comparative analysis of drag reduction efficiency through the use of surfactants and high molecular polymer additives has been performed. Results document that for polymer micellar solutions, the stable transitional zone between the laminar flow and the turbulent flow becomes extended towards higher Reynolds number values. The existence of a third extended drag reduction zone in the turbulent range of flow is also observed. It follows that the analysed polymer-micellar solutions combine and intensify positive features of their purely polymer and micellar analogues providing a more efficient drag reduction effect in wider range of flow.

Keywords: drag reduction, polymer, surfactant, aggregate, PEO, CTAB

Streszczenie

Zbadano efektywność redukcji oporów przepływu za pomocą jednoczesnego wprowadzenia do rozpuszczalnika polimeru i substancji powierzchniowo czynnej. Wykazano, że dla roztworów polimerowo-micelarnych stabilna strefa przejściowa pomiędzy ruchem laminarnym i turbulentnym zostaje wydłużona w kierunku większych wartości liczb Re. Zaobserwowano wystąpienie trzeciej, rozszerzonej strefy redukcji w zakresie turbulentnym. Wynika z tego, że analizowane roztwory, łącząc i potęgując pozytywne cechy ich czysto polimerowych i micelarnych odpowiedników, zapewniają efektywniejszą redukcję oporów w szerszym przedziale przepływowym.

Słowa kluczowe: redukcja oporów przepływu, polimer, SPC, agregat, PEO, CTAB

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Notation

c_f	– Fanning friction coefficient [–]
c_{fM}	– modified, pseudorheostable Fanning friction coefficient (5) [–]
d	– pipe diameter [m]
K	– fluid consistency constant [$\text{kg}\cdot\text{s}^{n-2}/\text{m}$]
L	– length of pipes measurement distance [m]
n	– flow behaviour index of power law fluid model [–]
ΔP	– pressure loss [Pa]
Re_M	– modified pseudorheostable Reynolds number (5) [–]
Re_S	– Reynolds number referenced to the pure solvent [–]
v_m	– mean velocity of pipe flow [m/s]
ρ	– solution density [kg/m^3]
ρ_S	– solvent density [kg/m^3]
η_S	– solvent dynamic viscosity [$\text{kg}/(\text{m}\cdot\text{s})$]

1. Introduction

Abnormal flow drag reduction through the use of surfactants or polymer additives is an effect which has been intensely examined and described in literature [1–6]. This phenomenon allows for increasing the flow rate without increasing power the demand, or vice-versa – reducing power demand while maintaining a constant flow rate. It provides potentially high possibilities for the application of this effect in different industry branches, particularly within the oil industry, heat engineering, fire fighting, and the transportation of slurries, sludge and brines [2, 7–9]. The causes of the described drag reduction have been associated with the existence of the new internal solution structure which formulates when special additives are mixed with the solution. The addition of high molecular weight polymer agents into the solvent results in a macromolecule structure formation [1, 6]. In cases where there has been the application of surfactants as drag reducing additives, the formation of micelle structures is observed [2, 5]. In the static condition, when the fluid is at rest, the above mentioned structures are chaotic. It is only during fluid flow shearing that both macromolecules and micelles start to arrange in characteristic orientation, in accordance with the principle of minimum resistance.

In order to improve the effectiveness of the micellarisation process, small amounts of electrolytes are added into the solution (e.g. sodium salicylate or sodium bromide). The effect of flow drag reduction through the use of high molecular polymer or surfactants has also some limitations. The main disadvantage of high molecular polymers is their susceptibility to mechanical and thermal degradation. In the case of surfactant solutions, it is the exceeding of a certain critical Reynolds number which results in the loss of micelles orientation and the collapse of the drag reduction effect.

The effect of the drag reduction induced by simultaneous addition of the high molecular polymer and the surfactant with salt into the solvent is still recent and poorly recognized. It is mainly internal structure formations and chemical reaction processes

in polymer-micellar solutions that are highlighted in a few published works related to this subject [11–14]. The first attempts of drag reduction effect experimental examination have been performed. Experimental results confirmed that the simultaneous addition of polymer and surfactant with salt into the solvent, combine and intensify positive features of their purely polymer or purely micellar solutions behaviour, providing extension of drag reduction zones [13, 14]. Nevertheless, the research pieces indicate that this new effect requires comprehensive experimental study in order to gain a deeper knowledge of this phenomenon.

The existence of polymer macromolecules in the surfactant solution enhances the ability of the surfactant to form micelles structures at a much lower concentration. The newly formed macromolecules are called aggregates [12, 13]. The addition of a small amount of salt (e.g. NaCl or NaSal) into the high molecular polymer and surfactant solution causes an increase in the size of micelles. It also increases the amount of micelles linked to the polymer chain. Furthermore, the addition of the salt can raise the solution viscosity.

The aim of this paper is to perform an analysis of drag reduction efficiency through the simultaneous addition of both surfactants and high molecular polymer into the solvent and compare with the drag reduction effect obtained by the application of the pure polymer or pure surfactant agents.

2. Internal structure characteristic of a polymer-micellar solution

The simultaneous addition of small amounts of polymer and surfactant into the solvent provides the initiation of micellarisation process at a much lower concentration in comparison with the critical micelle concentration (CMC). The concentration at which the initiation of micelle formation occurs in the presence of polymer macromolecules is called the critical aggregation concentration (CAC). The mechanism of the aggregates formation process can be illustrated in Fig. 1. The polymer chain structure is indicated with solid lines in the Figure. Remaining elements correspond to particles of the

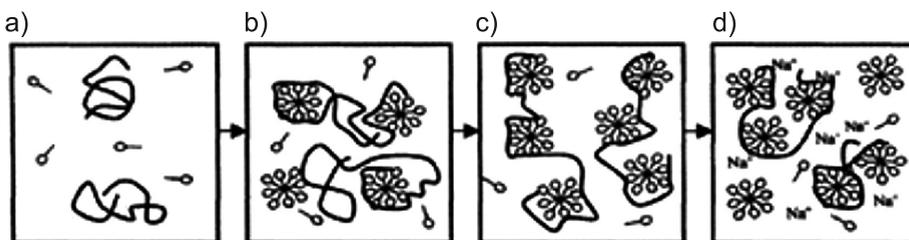


Fig. 1. Mechanism of polymer micelle aggregate formation [14]: a) Concentration of both polymer and surfactant additives is too low to induce interaction between additives molecules, b) Increase in concentration leads to micelles and aggregates structure formation, c) Polymer saturation point (PSP) – maximum viscosity value of mixture is reached, d) Further increase in solution concentration leads to the phenomenon of electrostatic screen; separate micelles are insulated

surfactant in the solvent. Initially, polymer and surfactant molecules occur in the solution independently. The situation significantly changes when a small amount of salt is added to the solution. According to [13, 15], salt causes surfactant micelle growth, as well as the linking of the polymer with surfactant micelles and the formation of aggregates through polymer molecules wrapping around the rod micelles. A consequence of this is an increase in the solution viscosity. It should be emphasized that the salt additive causes a significant viscosity increase. It is justified by more intensive interaction between polymer chains.

3. Materials and measurements

Having analysed the level of difficulty of planned experimental tests and taking into account the type of physical quantities to be measured, the experiment was performed using a modern capillary-pipe rheometer, designed and constructed in the Division of Fluid Mechanics laboratory in Cracow University of Technology [16]. After preliminary study, the following drag reducers were used for experimental analysis:

- non-ionic polymer with high molecular weight $M_v = 8 \cdot 10^6$ – poly(ethylene oxide) – $[\text{CH}_2\text{CH}_2\text{O}]_n$ (PEO)
- cationic surfactant – cetyltrimethyl ammonium bromide $[\text{CH}_3(\text{CH}_2)_{15}\text{N}(\text{CH}_3)_3]^+ + \text{Br}^-$ (CTAB)

In order to lower the CAC value, salt sodium salicylate $\text{C}_7\text{H}_5\text{NaO}_3$ (NaSal) was used. The mass fraction of the salt in the solvent was always twice as low as the mass fraction of the surfactant. Distilled water was used as the solvent. After the addition of the appropriate chemical drag reducers to the solvent, solutions were mixed gently so as not to cause mechanical degradation of polymer chains. Before taking measurements, mixtures were left to rest for 24 hours.

An analysis of drag reduction efficiency caused by a simultaneous addition of both surfactants and high molecular polymer into the solvent is conducted in contrast to corresponding effect obtained by addition of pure polymer or pure surfactant agents. 7 solution compositions with different concentrations were investigated. The designations and the compositions of the analysed mixtures are presented in Tab. 1.

Table 1

Summary of the analysed solutions and their designated rheological constants

Solution designation	Solutions composition	K [Pas ⁿ]	n
No. 1	30 ppm PEO	0.0011	0.9768
No. 2	100 ppm NaSal; 200 ppm CTAB	0.0031	0.8692
No. 3	200 ppm NaSal; 400 ppm CTAB	0.0089	0.7480
No. 4	30 ppm PEO; 100 ppm NaSal; 200 ppm CTAB	0.0053	0.7875
No. 5	30 ppm PEO; 20 ppm NaSal; 400 ppm CTAB	0.0113	0.6715
No. 6	60 ppm PEO; 100 ppm NaSal; 200 ppm CTAB	0.0031	0.8681
No. 7	60 ppm PEO; 200 ppm NaSal; 400 ppm CTAB	0.0058	0.8004

Adiabatic steady flow of homogenous solutions were examined in the temperature equal to 27°C. Fluid flow was performed in 8 different straight pipes having diameters ranging between 1.8 [mm] and 21 [mm].

4. Rheological characteristics and flow resistance measurements results

In order to identify rheological characteristics of the analysed solution, experimental/pipe-flow curves of analysed solutions were drawn in the form of the functional relationship described by the equation (1):

$$\tau_w = f(\Gamma) \quad (1)$$

where:

$$\tau_w = \frac{d\Delta P}{4L} \quad - \quad \text{shear stress at the pipe wall,}$$

$$\Gamma = \frac{8v_m}{d} \quad - \quad \text{pipe shear rate (value of shear rate on pipe wall).}$$

Interpretation of experimental results presented in the form of relationship (1) indicates that analysed solutions can be successfully approximated with the Ostwald – de Waele power law fluid model. Rheological parameters K (the fluid consistency constant) and n (the flow behavior index) for each of the analysed solutions are summarized in Tab. 1. Representative rheological characteristics in form of pipe flow curves are illustrated in Fig. 2.

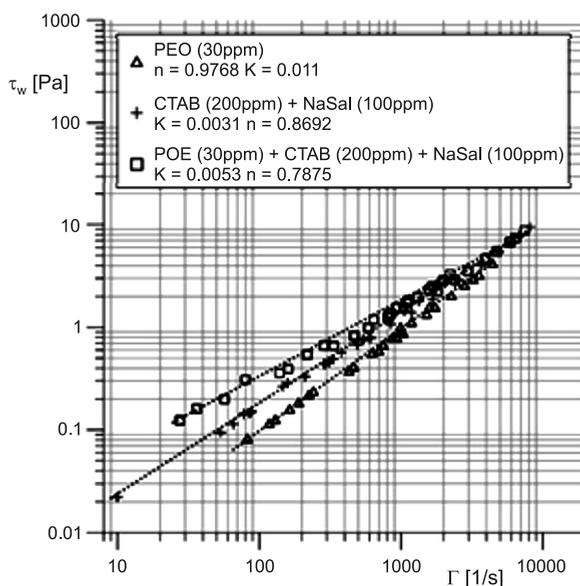


Fig. 2. Representative experimental flow curves for polymer, surfactant and polymer-surfactant solutions

The experimental results of the flow resistance are presented in the classical system of dimensionless numbers [Re_s, c_{fs}] described by formulas (2) and (3):

$$Re_s = \frac{v_m \rho_s d}{\eta_s} \quad (2)$$

$$c_f = \frac{d\Delta P}{2\rho v_m^2 L} \quad (3)$$

and additionally in the form of the drag reduction coefficient DR defined as a function of the Reynolds number (2), and prescribed in percentage terms:

$$DR = \left(1 - \frac{c_f}{c_{fs}} \right) \cdot 100\% \quad (4)$$

The analysis of the flow resistance curves reveals that none of the analysed flow range measurement points correspond to the theoretical functions which describe Newtonian fluid flow (Fig. 3). The simultaneous addition of even small amounts of high molecular polymers and surfactants causes an increase in flow resistance in the laminar range of flow. In the case of turbulent flow, the simultaneous application of the analysed chemical additives produces a drag reduction effect (Fig. 4).

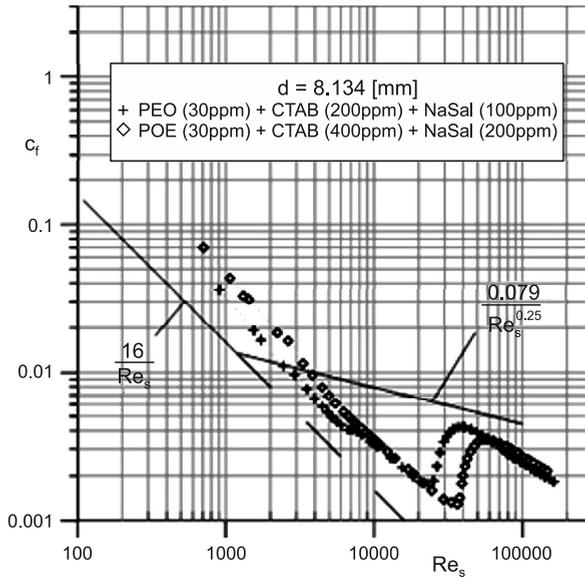


Fig 3. The flow resistance curves of polymer-surfactant water solutions defined in the system of cardinal numbers (2) and (3)

Furthermore, the value of the critical Reynolds number, for which transition from the laminar flow to the turbulent flow is observed, takes various values depending on pipe diameters, and the type and concentration of chemical additives introduced to the solvent.

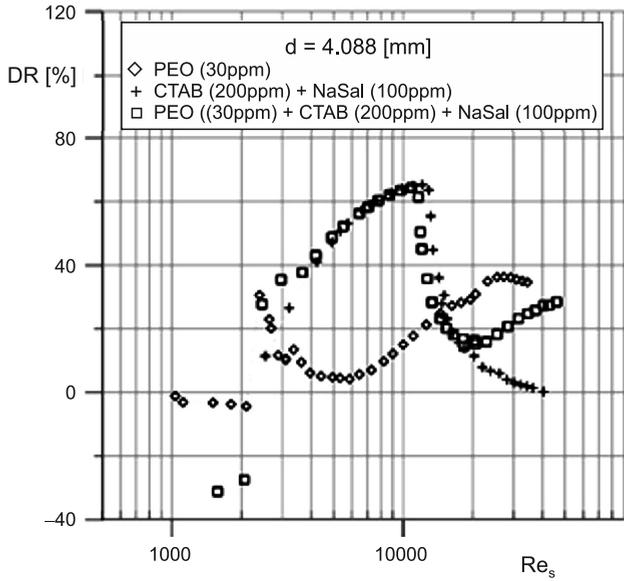


Fig. 4. The drag reduction coefficient curves $DR = f(Re)$

Better interpretation of the drag reduction phenomena can be achieved by presentation of the same measurement data in modified system of “pseud-Newtonian” [6] dimensionless numbers $[Re_M, c_{fM}]$, where:

$$Re_M = \frac{d^n v_m^{2-n} \rho}{K \left(\frac{3n+1}{4n} \right)^n 8^{n-1} \left[\frac{2(n+1)}{3n+1} \right]^{-2.5}} \quad (5)$$

$$c_{fM} = \frac{d \Delta P}{2 \rho v_m^2 L \left[\frac{2(n+1)}{3n+1} \right]^{2.5}} \quad (6)$$

Obviously [6], in so defined dimensionless number system, the flow resistance curves of purely viscous non-Newtonian fluids are transformed to the single curve – in the whole range of modified Reynolds number (5). Additionally, relationship (6) becomes identical to the classical Newtonian curves both in the laminar and turbulent flow ranges. The selection of such a coordinate system was dictated by the fact that it facilitated the identification and description of the characteristic drag reduction flow zones. In this modified system of pseudorheostable numbers $[Re_M, c_{fM}]$, each deviation of the experimental flow resistance curve that indicates abnormal drag reduction from pseudorheostable Blasius curve, allows the identification of the influence of specific additives (polymers or/and surfactants with salt) on the range of the analysed drag reduction effect. Fig. 5 presents the comparison of flow resistance curves in the modified number system (5) and (6) for the three analysed types of solutions with different internal structures. The results of the experimental data analysis indicate that polymer additives cause significant drag reduction in the turbulent range of

flow. Surfactant and salt additives (micellar solution) induce the appearance of a stable transitional zone in which a spectacular reduction of flow resistance is observed – usually greater in comparison with the same effect achieved with polymer additives. In this zone, the loss of stability of the laminar flow increases very softly, whereas the Reynolds number values grow – relative drag reduction is at its greatest within this range. After exceeding a certain second critical Reynolds number value ($Re_M > Re_{M2}$), the occurrence of an unstable transitional zone is observed. Within this range of flow, a rapid loss of the drag reduction effect occurs. Beyond certain third critical Reynolds number values ($Re_M > Re_{M3}$), the solution starts to behave like classical rheostable non-Newtonian fluid. The simultaneous use of polymer and surfactant with salt additives causes extension of a stable transitional zone in comparison with the same effect obtain with pure surfactant and salt additives. Additional abnormal drag reduction zone is observed in the turbulent range above Re_{M3} .

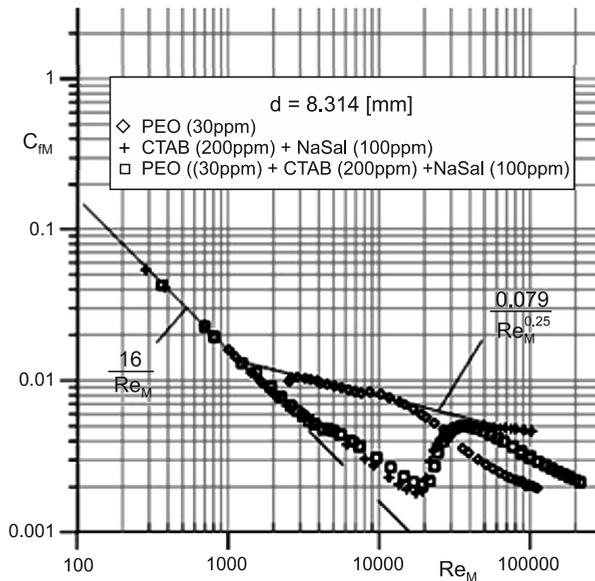


Fig. 5. The flow resistance curves of polymer, surfactant and polymer-surfactant water solutions, defined in the system of cardinal numbers (5) and (6)

The results of the drag reduction measurement analysis indicate the effect of pipe diameter change on drag reduction efficiency. Decreases in pipe diameter value d result in increases in the drag reduction effect in the turbulent range of flow.

5. Conclusions

Analysis of drag reduction efficiency by pure high molecular polymers, pure surfactants and mixed additives of polymer, surfactant and salt has been carried out. It indicates that multi-component solution of polymer, surfactant and salt causes increase of flow resistance in comparison with the pure solvent flow in the laminar range.

In the case of turbulent flow, the simultaneous application of the examined chemical additives produces a drag reduction effect. Significant extension of the stable transitional zone is observed between the laminar flow and the turbulent flow ranges. Surfactant with salt additives have the major influence on efficiency of drag reduction in this zone.

Experimental results prove that a simultaneous addition of surfactants and high molecular polymers into the solvent leads to the occurrence of a third significantly extended drag reduction zone in the turbulent range of flow. The viscoelastic characteristics of solution caused by the presence of polymer macromolecules play a crucial role in this zone. Increase in mass fraction of polymer additive result in increase in the efficiency of drag reduction effect only in the turbulent range of flow.

The performed comparative study indicates that the analysed polymer-micellar solutions combine and intensify the positive features of their purely polymer or purely micellar analogues providing a more efficient drag reduction effect across a wider range of flows.

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